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Remedial Response at the Richmond, California Hazardous Waste Site

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16. ABSTRACT

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REMEDIAL RESPONSE AT THE RICHMOND, CALIFORNIA HAZARDOUS WASTE SITE*

Municipal Environmental Research Laboratory, U.S. EPA

(*Received 30 June 1984*)

The U.S. Environmental Protection Agency surveyed 395 uncontrolled hazardous waste sites where some form of remedial action had been planned. A series of reports on 23 sites representative of various remedial response activities has been prepared. The current report from this series deals with the installation of a subsurface clay barrier wall and dike around an existing coastal landfill to prevent leachate from entering San Francisco Bay. Costs, equipment used and method of construction are reported in detail.

Key Words—Hazardous waste, landfill, clay barrier, leachate control, cost, San Francisco Bay, U.S.A.

1. Introduction

Richmond Sanitary Service (RSS) site is a commercially operated 350 acre (142 ha) landfill in Richmond, California. A 15 acre (6 ha) area of the site is used for disposal of Class I (hazardous) wastes, while the remainder of the landfill is used for Class II (non-hazardous) waste disposal. In 1975, the California Regional Water Quality Control Board (RWQCB) and the California Department of Health (DoH) found that the Class I area did not meet new state regulations regarding hazardous waste facility design and operation, and that the site posed a threat to surface waters, landfill employees, and air quality.

The site is located on San Pablo Bay at the outlet of San Pablo Creek. The State-designated beneficial uses of the bay and the creek area are: recreation, aquatic, waterfowl and migratory bird habitat; industrial water supply and navigation. Richmond Sanitary Service began accepting municipal and industrial wastes in 1952. In 1973, the RWQCB ordered RSS to designate separate areas for Class I and Class II wastes. The designated Class I section, consisting of a six-acre (2.4 ha) drum burial area and a 9 acre (3.5 ha) liquid waste evaporation pond, was situated on top of an older layer of municipal solid waste.

Throughout the early to mid-1970s, state agencies cited RSS for numerous health, safety, and air pollution problems at the site. Drums of solid and liquid chemical waste often ruptured while being dumped from trucks, and were not segregated according to compatibility. Volatile liquids were dumped in the evaporation pond, causing nearby residents to complain of chemical odors. In 1975, the RWQCB ordered RSS to make a number of operational and design improvements in both the Class I and Class II areas. Richmond Sanitary Service responded with an engineering master plan for the

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site proposing a much expanded Class I area enclosed by a relatively impermeable bay mud subsurface barrier. In March 1976, the RWQCB rejected the Class I expansion plan but ordered RSS to construct a subsurface barrier, a 2 ft high dike around the existing Class I area, and a basin to catch rainfall runoff and liquid waste overflow from the Class I area. Also in 1976, the DoH ordered RSS to improve waste handling and burial practices.

On 14 September 1976, RSS began construction of the subsurface barrier, the dike, and the retention basin using RSS' own earth-moving equipment and operators. The work was inspected by the engineering firm that designed the improvements. The 5 ft (1.5 m) wide barrier ranged from 5 to 30 ft (1.5 to 9.1 m) deep, and was 2765 ft (843 m) long. The new barrier was connected to 2100 ft (640 m) of a pre-existing barrier to completely enclose a 25 acre (10.1 ha) area containing the Class I pond, drum burial area, and retention basin. The construction took 28 days over a 7 week period, including 16 days for the barrier and 12 days for the dike and retention basin. Six months later, 10 monitoring wells were installed in the barrier.

2. Site description

The Richmond Sanitary Service site is an active landfill which is permitted to accept solid municipal wastes (Class II) and hazardous wastes (Class I) from the San Francisco Bay Area. Class I wastes are currently limited to contaminated solids in the barrel storage area and acid and caustic rinse water in the holding pond.

2.1. *Surface characteristics*

The site occupies approximately 350 acres (142 ha) of former marshland and tidelands adjacent to San Pablo Bay, in southwestern Contra Costa County. It is situated at

Fig. 1. Location of the Richmond Sanitary Service site, Richmond, California.

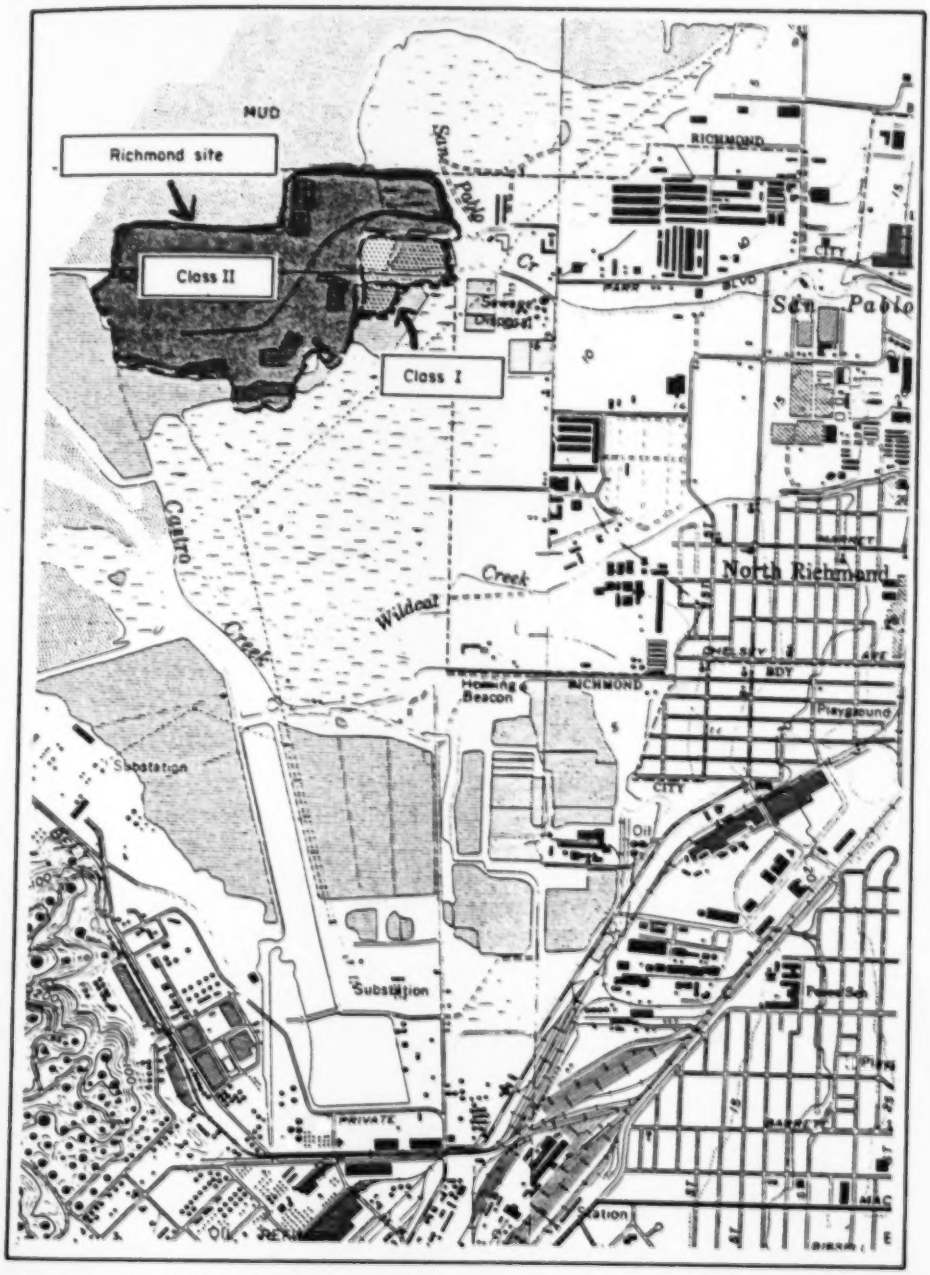

Fig. 2. Location of the Richmond Sanitary Services Class I and Class II disposal areas in Richmond, California.

the foot of Parr Boulevard in the City of Richmond and is bounded on the west and southwest by the Bay and on the north by San Pablo Creek. The San Pablo Sewage Treatment Plant is located just west of the site. The area is highly industrialized. A large refinery is located less than 1.5 miles (2.4 km) from the site boundaries.

Figures 1 and 2 show the location of the site. Figure 2 also shows the relative location of the Class I and Class II areas. The Class I area comprises only about 25 acres (10.1 ha) or about 7% of the 350 acre (142-ha) landfill.

Because the site is situated in former tidelands and marshlands of San Pablo Bay, potential for flooding has been a concern. However, as Fig. 2 illustrates, the Class I area is buffered from tidal action by the Class II area and by a perimeter dike. However, it should also be noted that lower San Pablo Creek closely parallels both the Class I and Class II areas along the northerly boundary of the site before emptying into San Pablo Bay. The magnitude of flood flow that reaches the Class I area is limited mainly by the channel capacity of San Pablo Creek and to a much lesser extent of Wildcat Creek.

The San Pablo Bay area has cool, dry summers and mild, moist winters. The mean annual temperature is 58.2°F (14.6°C). The mean monthly temperature ranges from a low of 50.2°F (10.1°C) in January to 65°F (18.3°C) in September.

The average annual precipitation in Richmond is 22 in (56 cm). The winters are moist and over 90% of the precipitation falls between November and May. Late in spring and summer coastal fog is common in the bay and usually clears by late morning. In winter, the relative humidity averages about 90% at night and 70% in the afternoon.

2.2. *Hydrogeology*

The site lies in an alluvial valley which is covered with Reyes silty organic clay soils which are nearly level, very poorly drained, highly compressible, and nearly impermeable. These soils are commonly called bay muds. The water table is at or near the ground surface.

The alluvial valley in which the Richmond Site is located is separated from the bedrock formations to the northeast by the Hayward fault. The San Pedro–San Pablo fault separates the valley from the bedrock formation to the southwest.

The Hayward fault, located approximately 1.3 miles (2.1 km) east of the site is seismically active and is one of the great earthquake faults in this part of California. The San Pedro–San Pablo fault is not considered to be seismically active. The San Andreas fault, although 16 miles (26 km) southeast of the site, is considered to pose a greater threat than the Hayward Fault.

A combination of driller's water well logs, foundation borings, water level records, etc. were used to construct a hydrogeologic cross-section of the area as shown in Fig. 3. The alluvial valley is underlain by a considerable thickness of unconsolidated sediments consisting of silty clay with interbedded layers of sand, shells, and peat. These bay muds, as they are called, occur to a depth of at least 50 ft (15 m) along the eastern boundary of the site and to at least 150 ft (46 m) along the western boundary as shown in Fig. 3. Lenses of sand found within the bay mud occur erratically and discontinuously. The bay mud is generally underlain by a sand unit deposited by stream channels which once traversed the area enroute to the Bay. These sand and gravel layers are sparse, highly variable in occurrence and generally only a few feet thick. These pervious layers are found mostly at depths below 100 ft (30 m) where they constitute what is referred to in Fig. 3 as the "deep aquifer zone". The zone constitutes the only productive

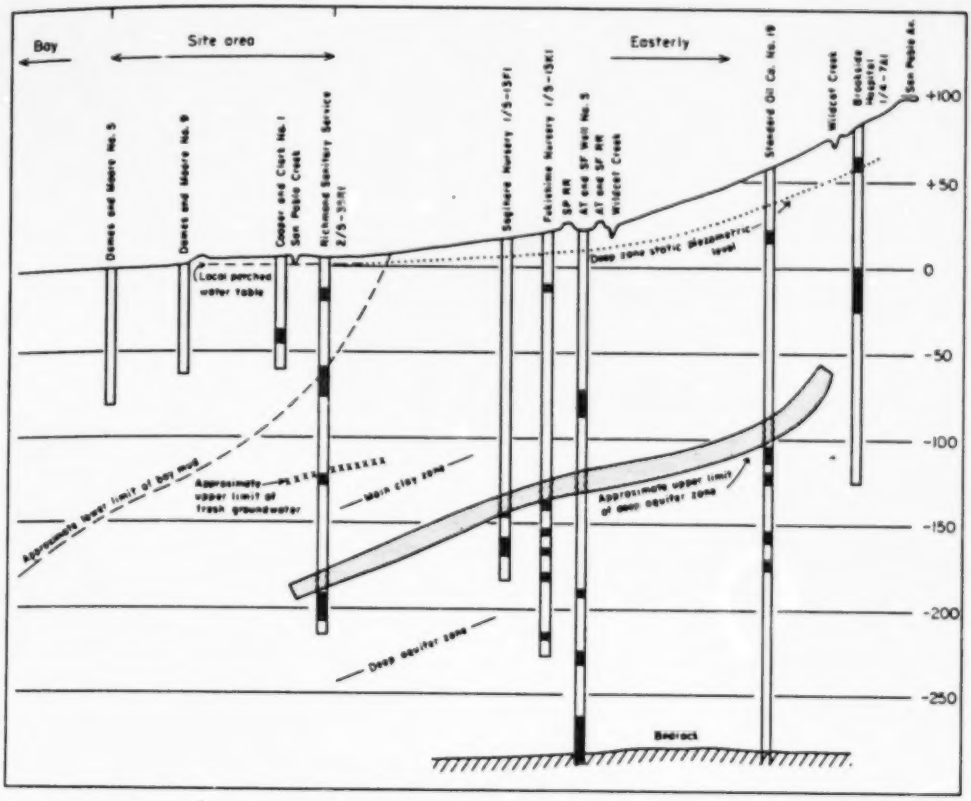

Fig. 3. Geological cross-section of the area around the Richmond Sanitary Services site: □, permeable sands and gravels; □, impermeable bay mud and clay; □, rock.

aquifer in the area. It is encountered at depths of 80–100 ft (24–30 m) several miles east of the study area but deepens to below 180 ft (55 m) in the vicinity of the site.

This sand layer in turn overlies an older bay deposit which consists of stiff, silty clay. Bedrock is estimated to underlie the site at depths of about 300 ft (91 m).

As shown in Fig. 3, most of the aquifer material is overlain by thick, clay zones which serve as aquicludes to confine these aquifers under artesian pressure. The groundwater in the area is replenished mainly from east of the project area where aquifers are not capped by impermeable clays and can receive surface water infiltration. The groundwater flows from these recharge areas towards the bay. At the RSS site, groundwater flow is in a westerly direction towards the bay but the hydraulic gradient is nearly flat and the rate of groundwater movement is very slow. Also, the highly impermeable bay mud and deeper clay deposits inhibit or greatly minimize lateral groundwater migration.

The capacity of the "deep aquifer zone" and the shallower sand lenses is rather limited since the zones are generally only a few feet thick and are discontinuous. Although well yields of 300–350 gal (1136–1325 l) per minute have been reported, the majority

pump much less. Some wells which penetrate the most productive aquifer zone have a maximum yield of less than 50 gal (189 l) per minute.

Water levels in both shallow and deep wells are generally quite shallow where not influenced by pumping. However, pumping records show drastic drawdowns in many cases and specific capacities are commonly only 1–2 gal min^{-1} of yield per foot (1.2–2.3 l min^{-1} of yield per metre) of drawdown.

Groundwater usage within the entire groundwater basin is very limited. There are no existing drinking water wells in the entire basin. In the locality of the site, aquifer zones located at depths of 50–100 ft (15–30 m) are known to be brackish and unsuitable for most uses.

3. Waste disposal history

The disposal practices at the Richmond site evolved over a 20–25 year period from haphazard, unregulated, dumping to carefully regulated and monitored disposal. This evolution paralleled the evolution of the State, and to a lesser extent, the Federal hazardous waste regulations.

Richmond Sanitary Service began acquiring the land currently used as a Class I and Class II disposal site in the early 1950s. In December of 1952, RSS was granted a land use permit by Contra Costa County for operation of a sanitary landfill. This permit, and a subsequent permit issued in 1960, placed minimal operational conditions for the handling of solid wastes, and handling of hazardous wastes was not addressed at all. As a result, throughout the 1950s and most of the 1960s RSS indiscriminately accepted hazardous wastes and took little or no precautions to protect public health, safety of the workers or the environment. Drums of wastes were often broken open, exposing workers and the public to flammable and toxic wastes. Incompatible wastes were not separated and volatile, toxic liquids were dumped indiscriminately. One of the few measures taken at the site during the 1950s was to construct a perimeter dike around much of the site.

In 1964, the Regional Water Pollution Control Board (predecessor of the present Regional Water Quality Control Board) issued a resolution requiring that disposal of solid municipal wastes and industrial wastes be done in a manner that is not detrimental to the state's waters. The Board established a self-monitoring programme for RSS and ordered that they construct a dike to prevent wastes from leaching into the Bay. However, the resolution did not establish any operational requirement for handling hazardous materials.

The 1970s marked the beginning of an increased awareness by the County and State of the problems at the Richmond Site. During 1970 about 1×10^6 gal (3.8×10^6 l) of hazardous wastes and approximately 120,000 tons (109,000 tonnes) of non-hazardous wastes were discharged at the site. In 1971, the RWQCB was granted authority to establish specifications for solid waste disposal sites, including design and construction of any measures needed to protect state waters. The RWQCB ordered that the suitability of areas used for disposal of Class I wastes be determined based on soil engineering, hydrologic and hydrogeologic studies. Richmond Sanitary Service's consultants, Cooper-Clark and Associates, conducted these studies and made several recommendations for upgrading the site. In 1973, the RWQCB issued an order to RSS which incorporated these recommended site improvements and identified a Class I area for disposal of hazardous wastes and a Class II area for solid municipal wastes. Because RSS encoun-

tered unanticipated problems in meeting the requirements of various governmental agencies, the Class I facility was not upgraded at that time.

The RWQCB was, however, investigating the site on a routine basis at this time. Several violations of the Board's order were documented. The most frequent violation was the deposition of hazardous wastes in the Class II area.

The state Department of Health (DoH) also investigated the site during the early 1970s and expressed concern over lack of precautions taken to ensure protection of workers and the public. Drums were still being disposed of haphazardly, incompatible wastes were not separated and volatile liquids were dumped indiscriminately. However, until the passage of the California Industrial Waste Act of 1972, neither the RWQCB or the Department of Health had the authority to control operational aspects needed to protect public health and the environment. The Industrial Waste Act required the Department of Health to develop a hazardous waste control programme by 1974.

In 1975, RSS submitted an engineering master plan for the site which proposed a much expanded Class I area enclosed by a bay mud subsurface barrier. In 1975 RWQCB rejected the expansion plan. They ordered RSS to construct the subsurface barrier, perimeter dike and retention basin. The Class I disposal area was upgraded between 1975 and 1978 to meet the requirements set forth by the RWQCB and the DoH.

4. Description of site investigation

As part of the RWQCB's requirements that Richmond Sanitary Service institute a self-monitoring programme to determine the acceptability of the site for handling Class I wastes, Cooper–Clark and Associates, under contract to RSS, conducted detailed soil engineering and hydrogeologic investigations of the site during 1971 and 1974. These investigations included the following activities.

(1) Exploration of soil and ground water conditions in the existing and proposed Class I areas to depths that could potentially be affected by wastes,
(2) Evaluation of physical characteristics of soil by laboratory testing and
(3) Determination of potential reaction of wastes with bay mud.

Soil borings were drilled at 100 ft (30 m) centres to depths ranging from 3 to 60 ft (1 to 18 m) using truck mounted, 5 in (12.7 cm) diameter rotary-wash equipment. Undisturbed soil samples were taken using split-tube barrel samplers for visual inspections and laboratory testing.

Borings taken around the perimeter of the existing Class I pond encountered about 3–13 ft (0.9–4.0 m) of loose, permeable refuse. In one area 5.5 ft (1.7 m) of chemical waste was encountered. The fills were directly underlain by bay mud containing varying amounts of sand lenses and peat. In contrast, very little refuse was encountered around what is now the barrel storage area, and the bay mud was relatively free of sand deposits at shallow depths. Groundwater was encountered within or above the fill in the existing filled area and near the ground surface in areas which remained unfilled.

Next, a series of soil engineering tests were performed on the bay mud on the sand lenses. Testing included the following.

(1) Permeability of natural bay mud deposits and compacted bay mud materials. Natural bay mud was found to have a coefficient of permeability of 10^{-7} to 10^{-8} cm s^{-1}.

Bay mud compacted to 80 per cent of maximum compaction at proper moisture content consistently had a permeability of 10^{-8} cm/sec.

(2) Determination of strength characteristics of bay mud using a portable Torvane Torsional Vane Shear test at natural moisture content. To aid in correlating the engineering properties of soil, moisture content and dry density tests were performed on all undisturbed samples.

(3) Grain size distribution tests on selected sandy soils.

This work showed that the bay mud was sufficiently impermeable to prevent leaching into the underlying ground water but that lateral seepage through the existing fill and sand lenses was a possibility.

Although the permeability of the bay mud was extremely low, there was some concern over the potential for changes in permeability due to reactions with highly acidic or basic Class I wastes. The results of laboratory tests on bay mud samples saturated with a pH solution of 2 and 10 showed no changes in consolidation or permeability characteristics. No such laboratory tests were conducted to determine changes in consolidation or permeability characteristics as a result of exposure to organics. However, samples of bay mud from the existing Class I area which had been in contact with various waste types were tested, and showed no apparent change in permeability.

5. Planning the site response

5.1. *Initiation of response*

In March 1976, the RWQCB ordered RSS to implement the site improvements in order to bring the facility into compliance with new hazardous waste disposal regulations. While no single incident triggered the order, problems over a 5 year period showed that the site posed an environmental threat. The order came after 6 months of negotiations between the RWQCB and RSS, during which RSS submitted proposals to greatly expand the Class I area pinto adjacent marshland and to construct a bay mud barrier enclosing the new Class I area.

The RWQCB rejected the expansion plans because RSS and the U.S. Army Corps of Engineers were then engaged in a dispute over the legitimacy of RSS' claim to title over the marshland. The RWQCB instead ordered RSS to construct the proposed barrier only around the existing 15 acre (6 ha) Class I area and an adjacent 5 acres (2 ha), which was to contain a retention basin for rainfall runoff from the Class I area and overflow from the Class I pond in the event of a dike failure. Figure 4 shows the layout of the Class I area.

5.2. *Selection of response techniques*

Based on detailed hydrologic, hydrogeologic and soil engineering studies, it became apparent that, although the low permeability of bay mud prevented vertical migration into underlying ground water, there was a potential for lateral migration into surface waters through existing refuse or sand lenses. These studies also indicated the potential for releases of hazardous chemicals in the event of flooding or seismic activity. The RWQCB ordered RSS to implement the following improvements.

(1) Construction of an underground, impermeable barrier which was to be keyed into the impermeable bay mud.

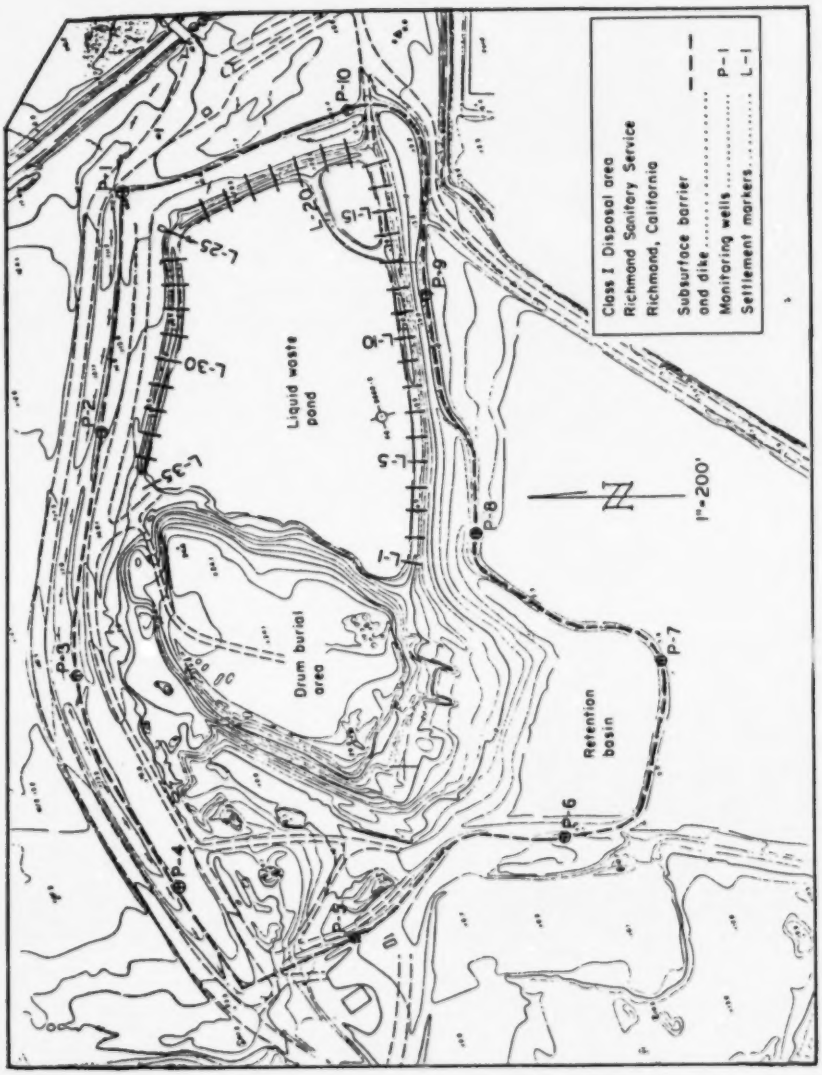

Fig. 4. Layout of the Class I disposal area.

(2) Construction of a perimeter dike surrounding the Class I area to prevent flooding.
(3) Construction and maintenance of a retention basin with adequate capacity to contain maximum runoff plus maximum volume of liquid which would escape the Class I pond in event of a dike failure.
(4) Installation of monitoring wells.
(5) Raising the interior dike around the Class I pond to provide sufficient elevation and slope to ensure stability in the event of seismic activity.

Inspections made by the Air Pollution Control District and the DoH throughout the early and mid-1970s and complaints from area residents of odours indicated that severe potential hazards still existed at the site. These included disposal of extremely hazardous chemicals, mixing of incompatible wastes, haphazard disposal of drums such that drums ruptured and leaked and lack of adequate safety precautions in handling wastes.

In November 1976, after the DoHs 1975 recommendation for operational improvements had not been implemented, the Department threatened issuance of a cease and desist order unless RSS made certain operational improvements. Richmond Sanitary Service initiated these improvements shortly thereafter, including separation of incompatible wastes in the barrel storage area and safer handling of drums and liquid wastes.

5.3. *Extent of response*

The RWQCB specified in its order to RSS that the sub-surface barrier be at least 5 ft (1.5 m) wide and have a permeability of not greater than 1×10^{-8} cm s^{-1}. The depth of the trench excavated for the barrier was to extend at least two feet (0.6 m) into the underlying layer of bay mud. The order further required that the 2 ft (0.6 m) high dike surrounding the Class I area be compacted sufficiently to meet the 1×10^{-8} cm s^{-1} permeability standard, that the retention basin be of a sufficient volume to contain any liquid waste release in the event of a failure in the Class I pond dike, and that 10 monitoring wells be installed at equal intervals in the barrier. The RWQCB based the design criteria on facility standards set forth in State hazardous waste facility regulations. Since the site rested on a 50–150 ft (15–46 m) thick layer of bay mud with a permeability of 10^{-6} cm s^{-1}, forming an effective aquiclude between the Class I wastes and the nearest useable ground water, State officials believed that the barrier would sufficiently mitigate the threat to State waters.

The order listed other operational improvements, requiring that 2 ft (0.6 m) of freeboard be maintained in the liquid waste pond, that each layer of buried drums be covered with at least 1 ft (0.3 m) of compacted soil, that the height of the drum burial area not exceed 43 ft (13 m) feet above sea level, and that the retention basin not be used for waste disposal.

6. Design and execution of site response

The response activities designed to prevent surface water contamination and to minimize the risk to public health and worker safety were implemented between 1976 and 1978. The activities were conducted and funded by RSS under the supervision of the RWQCB and the Department of Health.

6.1. *Construction of impermeable barrier, perimeter dike and retention basin*

In order to protect adjacent surface waters from pollution caused by lateral or vertical seepage, an impermeable, underground barrier was constructed around the perimeter of the Class I area, and the area was enclosed with a dike to protect against flooding and ensure containment of runoff. Both the underground barrier and the perimeter dike were constructed using bay mud excavated from the site. The inherently low permeability and ready availability made the bay mud an excellent choice for the barrier material.

RSS began construction of the site improvements on 14 September 1976 and completed most of the work by 30 October 1976. The specifications required that the underground impervious key was to be a minimum of 5 ft (1.5 m) wide and extend a minimum of 2 ft (0.6 m) below the refuse material where it was keyed into the underlying bay mud. Where sand lenses were encountered within 5 ft (1.5 m) of the bottom of the fill, the trench was to be excavated through the sand and 2–3 ft (0.6–1 m) into the underlying mud. The newly constructed barrier was also to be keyed into those portions of the barrier which had been constructed during previous years. The "old" barrier had been constructed along the northeast and south boundaries of the Class I Pond and along the western perimeter of what was later to be the retention basin. The new barrier was 2765 ft (843 m) long, and the old barrier was 2100 ft (640 m) long.

The trench was excavated using a hopto, which is a large, track-mounted backhoe. Although the trench was required to be only 5 ft (1.5 m) wide, it sometimes reached 8–10 ft (2.4–3.0 m) wide in areas of heterogeneous refuse fill. During excavation, the backhoe encountered a considerable amount of refuse as well as demolition debris, chemical waste and drums. These materials were removed from the trench and disposed of in the Class II area. At one point during trench excavation, flammable liquids were encountered and the trench caught fire. No safety equipment was worn by field personnel despite the fact that hazardous materials were encountered. Because of the considerable thickness of refuse and sand lenses encountered, it was necessary to excavate the trench to depths of 20–30 ft (6–9 m) in some areas. The backhoe had a reach of only about 20 ft (6.1 m). Consequently, it was sometimes necessary to use a track-type dozer to excavate about 10 ft (3.0 m) below grade adjacent to the trench to serve as a temporary working area for the backhoe so it could excavate to the required depths.

Inflow of water into the trenches was another problem encountered during excavation. Inflow was particularly rapid in areas of more permeable refuse fill, and in the area of the Class I pond due to seepage of liquid wastes. However, the need for dewatering was eliminated by excavating and backfilling in about 30 linear ft (9 m) segments, avoiding long lenghts of unsupported open trench.

A dragline was used to excavate the bay mud used for backfill from an area southeast of the retention basin. In some areas sand lenses were encountered and this material, unsuitable for backfilling, was discarded.

It was necessary to closely coordinate the rate of trench excavation and backfilling. If the excavation proceeded too far ahead of backfilling there was likely to be considerable inflow of water into the trench and dewatering would be needed. If, on the other hand, hauling of the bay mud for backfilling proceeded too far ahead of excavation, the material would be unsuitable for backfilling because it was required that it be dumped at its natural moisture content without letting it dry.

Samples from the completed barrier had permeabilities of the order of 10^{-8} cm s^{-1}.

Following completion of the key, RSS began construction of the above ground perimeter dike. The perimeter dike was constructed to a height of about 2 ft (0.6 m) above ground level which was considered adequate to prevent Class I area runoff from entering the Class II area. The completed dike area was 4900 ft (1494 m) long.

Again, bay mud was hauled in trucks from the area southeast of the retention basin. Large track-type bulldozers were used to roughly shape the slopes of the earthworks. Smaller bulldozers, equipped with extra wide tracks, were used for finishing the slopes. The dike was compacted to at least 80% of maximum density in order to attain the required permeability of 10^{-8} cm s^{-1}.

6.2. *Installation of monitoring wells*

In July 1977, Cooper–Clark installed ten monitoring wells at equal distances within the containment structure enclosing the Class I areas. The wells were drilled with a truck-mounted 7 in (17.8 cm) diameter, rotary wash drill rig approximately along the centreline of the containment structure. The wells extended through the existing bay mud key and at least 1 ft (0.3 m) into the natural bay mud. The depth of the wells ranged from 10 to 13.5 ft (3.0–4.1 m). It was essential to install the wells within the barrier so that wastes which had been disposed of outside of the barrier limits during the 1960s and early 1970s would not be detected during monitoring.

After drilling each well, a 4 in (10.2 cm) diameter, perforated PVC pipe surrounded by at least 1 in (2.5 cm) of filter material consisting of 1 in (2.5 cm) maximum size pea gravel was installed. A cap was provided for each pipe, and the top 2 ft (0.6 m) of backfill around the pipe consisted of impermeable bay mud to prevent surface water infiltration into the well. These wells are monitored quarterly by EMCON Associates and the data is submitted to the RWQCB.

6.3. *Class I pond*

During late 1976 and early 1977, the 9 acre (3.6 ha) Class I liquid pond came under critical examination. The pond was filling up and the 2 ft (0.6 m) freeboard limit placed on it by the RWQCB was exceeded. On 4 January 1977, the RWQCB ordered RSS to stop placing waste in the pond.

The reason the pond exceeded its freeboard limit was apparent. Prior to installation of the underground barrier, the pond acted as an infiltration basin, allowing the liquid wastes to seep into the old underlying refuse. Construction of the barrier in October 1976 severely restricted further infiltration. Also a persistent layer of 2–5 in (5–13 cm) of oil on the pond prevented the liquid from evaporating.

In order to meet the requirements for a minimum of 2 ft (0.6 m) of freeboard, it was necessary to raise the crest of the perimeter dike to an elevation of 21 ft (6.4 m). The RWQCB granted permission to raise the elevation provided the following stipulations were met.

(1) The permeability of the dike was not to exceed 10^{-8} cm s^{-1}.
(2) The crest width was to be at least 5 ft (1.5 m).
(3) Inboard and outboard slopes could not be steeper than 3:1 (horizontal:vertical) to assure slope stability in the event of seismic activity.

The crest of the dike surrounding the pond was elevated using procedures similar to those used for constructing the perimeter dike.

Following completion of the dike, the RWQCB required that permanent settlement bench marks and liquid gauges be installed at equidistant intervals around the perimeter of the pond. The settlement bench marks consisted of nine capped steel pipes driven into the top of the dike at 200 ft (61 m) intervals. The liquid gauges consisted of four welded steel staff gauges which were installed at 400 ft (120 m) intervals. The top of the gauges were set at elevation 21 ft (6.0 m) to allow a direct reading of the pond freeboard relative to the top of the dike.

6.4. *Loading rate determinations*

Elevating the crest of the dikes to 21 ft (6.4 m) was not sufficient justification for reopening the Class I pond. The RWQCB required that RSS conduct an evaporation rate study in order to determine the liquid loading rate which could safely be accepted. They also required documentation that the retention basin located south of the barrel storage area had sufficient storage capacity to contain runoff and any conceivable discharge from the pond in the event of a failure of the perimeter dike.

Initially it was estimated that 730,000 gal (2.8×10^6 l) of liquid per month evaporated from the pond. However, the RWQCB considered this rate to be very optimistic. It assumed that the evaporation rate from the pond would be equivalent to pure water. This assumption was not true since, as the salt concentrations increased within the pond, surface tension increased and evaporation decreased. Also the industrial discharge to the pond typically contained substantial amounts of floatable oils which effectively prevented evaporation from the surface.

The RWQCB therefore recommended that the actual evaporation rates be monitored. Cal Recovery System Inc. made actual measurements of the evaporation rates between December 1977 and May 1978. Based on these studies they concluded that an acceptable loading rate was 500,000 gal (1.9×10^6 l) per month, provided that the pond was cleaned periodically and that the rate be adjusted to reflect any unusual conditions such as very heavy rains or excessive oil and debris. This loading rate met with the approval of the RWQCB provided the 2 ft (0.6 m) minimum freeboard was maintained.

The next task was to determine the adequacy of the retention basin to contain Class I liquids in the event of a dike failure around the Class I pond. To answer this question, it was necessary to define a conceivable dike failure. There was no possibility of failure to the north, west, and most of the east of the perimeter dike owing to the configuration of the adjacent ground. However, in the event of the maximum credible earthquake along the San Andreas Fault, there was the possibility of lateral movement along the southern perimeter of the pond but not complete dike failure.

Cooper–Clark determined the stability of these slopes in the event of seismic activity using the "SHAKE 2" computer model made available through the University of California at Berkeley. It was later confirmed using the results of the more complete "LUSH" programme.

Assuming the most severe set of circumstances; that is a maximum lateral movement of the southern perimeter dike and maximum runoff resulting from a 100 year storm of 24 h duration, it was determined that the retention basin would be filled only 61% of its capacity or 3.6×10^6 gal (13.6×10^6 l). Therefore, the capacity of the retention basin was considered adequate.

6.5. *Implementation of waste management practices for the class I evaporation pond and retention basin*

Following completion of these remedial measures the pond was reopened. The RWQCB stipulated that RSS could accept up to 500,000 gal (1.9×10^6 l) per month (provided a minimum 2 ft freeboard was maintained) of Class I liquid wastes with the exception of pesticides, paint sludges, solvents, tetraethyl lead sludge and oil, which cannot be accepted. The pH of the pond is now maintained near neutrality due to a balance of caustic and acid wastes.

In order to insure a minimum freeboard of 2 ft and to optimize evaporation, the pond is periodically skimmed to remove oils and animal fats which rise to the surface as a result of their disposal in the 1950s and 1960s. Skimming is only required infrequently when about 20% of the pond is covered with oil. The oil is pumped into a small adjacent pond and is later sold for fuel.

Finally the liquid level in the retention basin must be maintained such that sufficient capacity exists to store liquids from the Class I pond in the event of a dike failure. In order to ensure this capacity, rainwater is periodically pumped from the retention basin directly to the San Pablo Sewage Treatment Plant for treatment. Richmond Sanitary Service has an agreement with the treatment plant whereby the landfill accepts secondary sewage sludge from the treatment plant in exchange for free treatment of the retention basin effluent. The effluent from the retention basin can be discharged directly into the bay if it meets minimum discharge requirements.

6.6. *Implementation of remedial measures and waste management practices for the barrel storage area*

In 1976, both the RWQCB and the DoH issued requirements for upgrading the barrel storage area. The RWQCB required that RSS submit a slope stability analysis for the slopes around the barrel storage area specifying the maximum slope and height of fill which could be developed without exceeding 80% of the shear strength of the underlying material. Slope stability was determined using the previously mentioned "SHAKE 2" and "LUSH" methods of analysis and assuming the maximum credible earthquake along adjacent portions of the San Andreas Fault. Based upon this analysis Cooper–Clark concluded that the maximum allowable slope should be 8:1 except for the easterly slope adjacent to the Class I pond, which should not be steeper than 4:1. The RWQCB also required that the barrel storage area not have an elevation greater than 43 ft (13 m) above mean sea level to further assure slope stability.

During the later months of 1976 and in early 1977, RSS instituted numerous operational improvements for the barrel storage area as required by the DoH. Bay mud and other clays were used to construct four separate barrel disposal cells for each of the following categories of waste: acids; alkalies and cyanides; strong oxidizers; and pesticides, solvents and organic chemicals. The cells were separated with a minimum of 5 ft (1.6 m) of clay or bay mud.

Special equipment was purchased so that drums could be unloaded and disposed of without damage. Equipment operators were required to wear respirators and safety shields were installed on the front of drum unloaders.

In February 1980, DOH ordered implementation of additional measures to upgrade the barrel storage area. These measures included the following.

(1) Bury the containers with a volume of soil sufficient to absorb the total volume of liquid in the drum.

(2) Completely cover the drums with earth at the end of the day.

(3) Provide a minimum of 1 foot (0.3 m) of compacted soil prior to starting the next layer.

Rather than meet these requirements, RSS stopped accepting drums containing more than 10% liquids. They are currently accepting bulk or containerized contaminated soils or solids. A closure plan has been developed for the barrel storage area.

7. Cost and funding

7.1. *Funding*

Richmond Sanitary Service paid for construction of the site improvements out of its operating budget and used its own equipment and staff to implement these, Cooper–Clark and Associates were used as consultants.

7.2. *Project costs*

While RSS made a number of site improvements from 1976 to 1978, this cost analysis focuses only on the major actions: the barrier, the perimeter dike, and the retention basin. Because RSS primarily used its own workers and equipment for the project, invoices were not available with which to calculate the precise cost of the work. Operators and earth-moving equipment were borrowed as needed from the daily landfill operations. Consequently, an estimate of the cost of implementing the site improvements was based on standard rates. Since all of the bay mud used for the site improvements was taken from other areas of the landfill, the only material costs were for monitoring wells.

While the work occurred in 1976, 1983 rates were used to estimate the cost of the project, in order to make the costs more current. It is important to note that the estimated costs were based on limited data, and may vary from the actual cost by as much as 30%. The rates used were taken from *Mean's Building Construction Cost Data* (1983). Most of the costs were calculated from bare cost rates for daily equipment rental, hourly operating cost, and hourly labour, without including overhead and proft. However, since RSS hired trucks from outside to haul mud, the hauling estimate includes over-

TABLE 1
Summary of cost information—Richmond Sanitary Service, Richmond, California

Task	Quantity	Expenditure (1983, U.S.$)	Unit cost	Period of performance
Constructing subsurface barrier	7313 yd^3 (5592 m^3)	$56,118	$7.67 yd^{-3} ($10.03 m^3)	14 Sept.–13 Oct. 1976
Constructing dike, basin	—	$20,718	—	18 Oct.–19 Nov. 1976
Site investigation and design	—	$15,000	—	1976
Installing monitoring wells	10 Wells	$15,000	$1500 $well^{-1}$	28 June–7 July 1977
Inspection oversight of construction	30 Days	$4200	$140 day^{-1}	14 Sept.–9 Nov. 1976
Total cost		$111,036		

head and profit, and was calculated on a per-cubic-yard basis. A summary of the cost is provided in Table 1.

The total cost of constructing the 2765 ft (843 m) long subsurface barrier, the 4900 ft (1494 m) long, 2 ft (0.6 m) high compacted mud dike, and the 5 acre (2 ha) retention basin was about $111,000, in 1983 dollars. The bulk of the cost, about $77,000, was for excavation and earth moving. The remaining $34,000 was for Cooper–Clark's engineering services.

8. Performance evaluation

Based on all indications, the response activities undertaken at Richmond Sanitary Service have been effective in controlling migration of contaminants and in protecting public health and worker safety. By installing a system of dikes and an underground barrier composed of bay mud, RSS was able to take advantage of the low permeability of the natural silty clays found beneath the site to effectively control the source of contamination at a relatively low cost. The bay mud barrier and dikes were such logical choices for the response technology that no other technologies received serious consideration.

Available monitoring data verifies the performance of the barrier. As of August 1982, groundwater monitoring has not detected any leakage of contaminants through the underground barrier. Another indication of the effectiveness of the barrier is the fact that the Class I liquid waste pond began to fill up rapidly after the barrier wall was completed. Prior to construction of the barrier, the Class I pond was acting as an infiltration basin allowing liquid wastes to seep into the underlying landfill. The barrier has restricted further infiltration.

The dikes surrounding the Class I area have generally been effective in controlling runoff and flood waters. However, in February of 1980, there was a failure of the dike surrounding the retention basin during an intense rainstorm. This dike was redesigned and reconstructed and no further problems have been reported.

There is no information on the volume or type of contaminants which may have been dumped outside of the underground barrier prior to its construction and the extent to which these contaminants may be migrating into San Pablo Bay. However, the potential for migration into the bay has been greatly minimized by construction of a second barrier around the entire perimeter of the 350 acre (142 ha) site. This barrier was required to have a maximum permeability of a 10^{-6} cm s^{-1} as compared to 10^{-8} cm s^{-1} for the Class I barrier.

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